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AIRCRAFT DIRECTIONAL STABILITY AND CONTROL: NEW IMPROVED APPROACH IN TAIL DESIGN

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ABSTRACT

This work deals with a review and proposed improvements of vertical tail classical design methods dealing with aircraft directional stability and control.
The research presented is based on many numerical and experimental results obtained by the authors (DAF research group, www.daf.unina.it) through both CFD calculations and wind-tunnel tests carried out on an aircraft modular configuration. A new improved methodology to predict the directional stability and control characteristics of an aircraft and a reliable sizing procedure for the vertical tail is proposed. The methodology obtained and all results are particularly relevant for the regional turboprop category, but they can also be applied to other transport aircraft configurations. A wind tunnel investigation involving more than 150 configurations has also been involved in order to validate the numerical approach for which about 200 configurations were involved. The analyses covered both the linear and the non-linear range of the aerodynamic coefficients.

Keywords: Aircraft Directional Stability, Vertical Tail Design, CFD, Wind-Tunnel tests

1 INTRODUCTION

The aircraft vertical tail is the aerodynamic surface that must provide sufficient directional equilibrium, stability, and control to the aircraft. Its sizing is determined by critical conditions as minimum control speed with one engine inoperative (for multi-engine airplanes) and landing in strong crosswinds conditions.

The *airborne minimum control* speed V_{MC} is the calibrated airspeed at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane with that engine still inoperative and maintain straight flight with an angle of bank of not more than 5° [1]. The airborne minimum control speed may not exceed 1.13 times the reference stall speed. Thus, it affects the takeoff field length, which must be kept as low as possible otherwise payload could be reduced when the aircraft is operating on short runways. The V_{MC} involves large rudder angles δ_r to keep a small angle of sideslip β. See Figure 1 left. This requires a certain vertical tail area for a given rudder effectiveness τ, which must be the highest possible to keep control authority at 25° or more of rudder deflection.

A *crosswind landing* requires also a correct sizing of the vertical tailplane and rudder to ensure the possibility to fly with large sideslip angles β in full flaps conditions. The rudder efficiency should allow the aircraft to keep the airplane at the desired flight path, although the rudder deflection is usually opposed to the sideslip angle, such that the vertical tail lift curve is in the linear range (like a plain flap at negative angle of attack, see Figure 1 right). While for

the V_{MC} condition the engine position and power leads to a certain sizing of the vertical tail are and rudder dimension, the crosswind landing condition involves also the whole aircraft directional stability. It will be shown in the last part of the article that an oversize of the vertical tail (high directional stability) would lead to the impossibility to fly under certain sidewind conditions.
This clearly highlights that the design and sizing of the vertical tailplane is not trivial and only a balanced sizing can lead to good flight characteristics in all flight conditions.

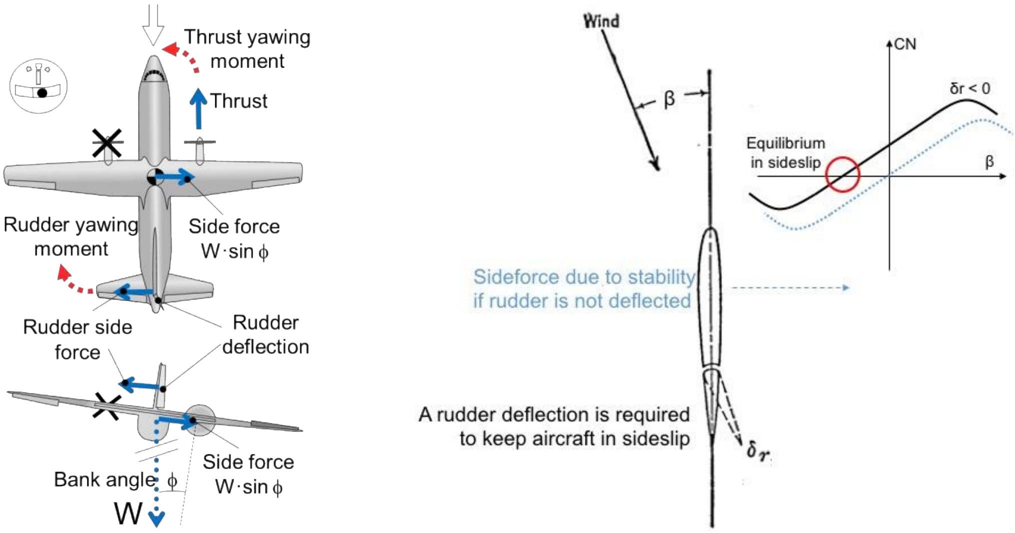


Figure 1: Aircraft directional control in action with one engine inoperative (left, ©Harry Horlings / Wikimedia Commons / CC-BY-SA 3.0) and rudder deflection to keep a given sideslip angle (right).

Concerning aircraft directional stability, the derivative of the complete aircraft is usually depending on the addition of several contributions, due to different aircraft component. Usually, neglecting the horizontal tailplane and nacelle contributions, the main contributions are due to the fuselage and the vertical tailplane, with a contribution coming from the wing (in case of a swept wing). The effect of the wing is directly relevant only for moderate to high sweep angle, whereas both wing and horizontal tail have a significant *indirect* effect due to the aerodynamic interference on the vertical tail.
In general the directional stability contribution due to the vertical taiplane is strongly influenced by indirect interference effects due to the interference effects of fuselage, wing and horizontal tailplane on the vertical tailplane efficiency. Also the fuselage contribution can include an interference effect mainly coming from the presence of the vertical tailplane on the rear part of the fuselage which strongly modifies the pressures on the fuselage tail just below the fuselage with respect to the pressures and directional instability of the isolated fuselage. So, assuming that each term includes also the interference effects, the complete aircraft directional stability derivative becomes :

$$C_{N_\beta} = C_{N_{\beta_v}} + C_{N_{\beta_f}} + C_{N_{\beta_w}} \quad (1)$$

The previously mentioned interference effects have been highlighted also by classical semi-empirical methodologies well-known as a reference for directional stability prediction such as USAF Datcom (also reported by Roskam books) and ESDU see [2, 3, 4].
The interference effects of fuselage, wing, and horizontal tail on the vertical tail can be highlighted through the following considerations:

- the fuselage in sideslip conditions exhibits a flow characteristic similar to a cylinder in airflow, where the peak local velocity occurs at the top at the cylinder and it decays to the free stream *cross-flow* value at distance from the body surface. This phenomenon tends to increase the effectiveness of the vertical tail: the fuselage directly alters the vertical tail incidence because of the cross-flow around the body. Hoerner [5] has given another physical explanation: the fuselage acts as an *end-plate* on the vertical tail, being similar to a combination of a wing with a tip tank. Both theories neglect the effect of the vertical tail on the fuselage. The investigation performed by the authors also highlighted that the vertical tail reduces the fuselage instability in sideslip, especially in the non-linear range of the lift curve;
- the vortex system developed by the wing-fuselage combination in sideslip, named *sidewash* and analogous to the downwash in the longitudinal plane, indirectly affects the incidence of the vertical tail. This effect is such to increase the vertical tail contribution to directional stability if the wing is low with respect to the fuselage; the contrary happens on a high wing-body combination;
- the effect of the horizontal stabilizer on the vertical tail is a change in the pressure loading of the latter, if the former is located at a relatively high or low position. Test data highlight the greater effectiveness of vertical stabilizer in these configurations, a phenomenon named *end-plate effect*. Conversely, a reduction of vertical tail contribution to directional stability is observed if the empennage assumes a cruciform shape.

However, the authors have been investigating in previous articles the accuracy of the above mentioned methods on several aircraft configurations, highlighting that in some cases both DATCOM and ESDU lead to wrong and even dissimilar results, see[6-8]. For example the interference effect of the horizontal tailplane on the stability contribution of the vertical tailplane seems not correctly predicted in some cases (position of the horizontal tailplane) and the two methods show an high degree of discrepancy between them, as reported in Figure 2, where the vertical tail stability derivative computed with both methods is plotted w.r.to the vertical position of the horizontal tailplane.

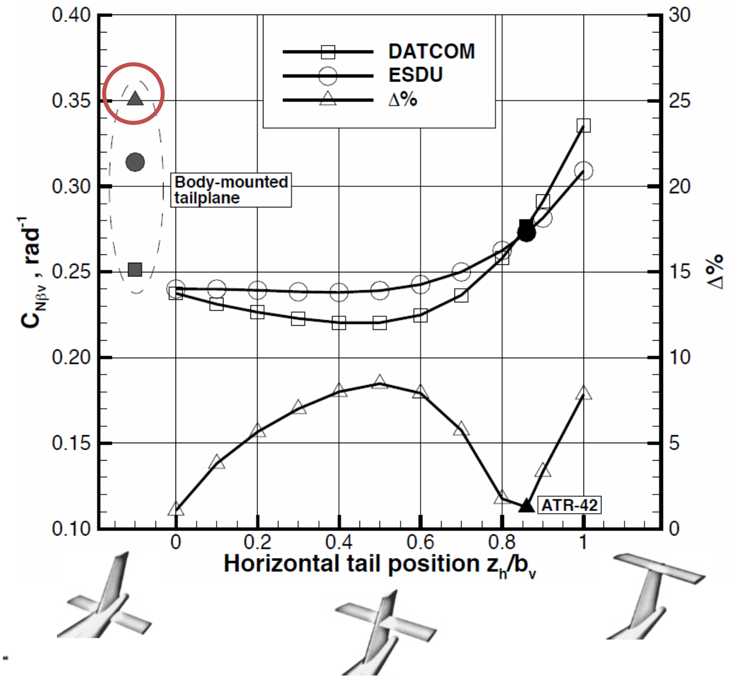


Figure 2: Parametric investigation to compare semi-empirical methods.

In case of a classical body-mounted configuration the difference between the two methods is higher than 20%. Also the T-tail configuration would present a difference higher than 10%. Only for two configurations, with the horizontal tailplane mounted at the root of the Vertical tailplane ($z_h/b_v=0$) and with the horizontal tailplane mounted at about 85% of the vertical tail span(configuration typical of ATR regional turboprop aircraft) the difference is lower than 5%. The Datcom method, as also well explained by the authors in [6], were obtained in the 40's by NACA through several wind-tunnel tests performed on aircraft configurations similar to a military fighter (low AR and high sweep) and so it is quite evident that those old methodologies cannot be so accurate in prediction of stability derivative of regional transport turboprop aircraft.
The ESDU and DATCOM methodologies model the interferences with a modification of the effective vertical tail Aspect Ratio (AR_v) which is the most important parameter for the estimation of vertical tail lift curve slope.

2 THE NEW PROPOSED METHODOLOGY

The authors have been working to the development of a new methodology to estimate the vertical tail contribution to the aircraft directional stability particularly addressed to regional turboprop aircraft configuration. The methodology have to be fast and reliable, also including all the interference effects described in the Introduction and usually included in other semi-empirical methods. The idea is to build a reliable methodology with an high degree of accuracy for regional turboprop configurations.

2.1 The modular model

In order to build this new methodology, a modular regional turboprop model (or configuration) has been conceived. The modularity is essential in order to capture all the above mentionaed interference effects. In particular the wing effect (usually referred as downwash) is strongly dependant on the wing-fuselage relative position (and with a light effect of wing AR).
The fuselage interference effect will be dependent on the ratio of the vertical tail span to the fuselage diameter in the vertical tail region (b_v / d_f) and on the fuselage tailcone upsweep angle. To this aim a modular model has been built.
Through the variation of the vertical tail span, taper ratio and sweep angle, through the modification of the tailcone upsweep angle, through the variation of wing position and wing AR through the variation of horizontal tailplane dimension and position (see Figure 3) more than 150 different configurations can be obtained and used to estimate the interference effects.

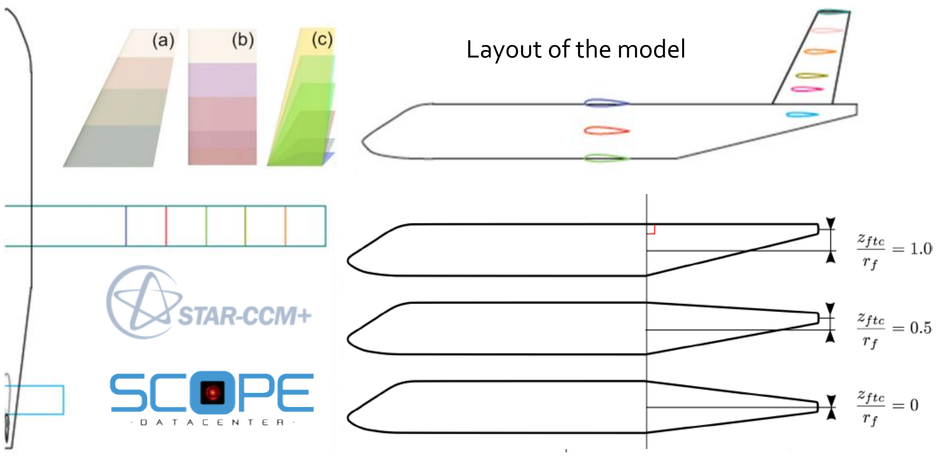


Figure 3: Layout of the aircraft modular model used to develop the new method.

The first phase has been characterized by a deep CFD campaign performed through a CFD solver and using the University of Naples parallel grid computing network (Scope). The aerodynamic analysis performed have been addressed to the estimation of the stability derivative of all configurations and consequently the possibility to estimate the interference factors just comparing the results w.r.to the isolated vertical tailplane.

2.2 The new methodology - implementation

Through the CFD analysis of more than 150 different configurations analysed in low to moderate sideslip angle condition (β <10 deg.) the directional stability derivative has been extracted and the coefficients showing the interference effects have been calculated and plotted w.r. to some relevant geometrical parameters (effect of relative dimensions among components or component relative position).
The new methodology will estimate the vertical tail stability derivative with the formula reported in (2).

$$C_{N_{\beta_v}} = K_{F_v} K_{W_v} K_{H_v} C_{L_{\alpha_v}} \frac{l_v}{b} \frac{S_v}{S} \tag{2}$$

where the correction factors *K* have been extracted from the results of all CFD analysis comparing the obtained result (the obtained derivative) to a reference value characteristic of the isolated vertical tailplane contribution.
In particular :

K_{F_v} is the aerodynamic interference factor of the fuselage on the vertical tail;
K_{W_v} is the aerodynamic interference factor of the wing on the vertical tail;
K_{H_v} is the aerodynamic interference factor of the horizontal tail on the vertical tail;

$C_{L_{\alpha_v}}$ is the lift curve slope of the isolated vertical taiplane that can be computed with several available formula and will be mainly dependent on vertical tail AR and sweep ;

$\frac{l_v}{b}\frac{S_v}{S}$ is the vertical tail volume coefficient.

The interference factor due to the fuselage is defined as the ratio of the vertical tail stability derivative of the fuselage-vertical tail combination (FV) to the isolated vertical tail (V). Similarly, the interference factor due to the wing is given by the same ratio calculated for the wing-fuselage-tail combination (WFV) against the fuselage-vertical tail configuration (FV). Finally, the effect of the horizontal tail is evaluated by the ratio of vertical tail stability derivative of the complete aircraft (WFVH) against the wing-fuselage-vertical tail combination (WFV). In mathematical expressions :

$$K_{F_v} = \frac{C_{N_{\beta_v}}(\mathrm{FV})}{C_{N_{\beta_v}}(\mathrm{V})} \qquad K_{W_v} = \frac{C_{N_{\beta_v}}(\mathrm{WFV})}{C_{N_{\beta_v}}(\mathrm{FV})} \qquad K_{H_v} = \frac{C_{N_{\beta_v}}(\mathrm{WFVH})}{C_{N_{\beta_v}}(\mathrm{WFV})} \tag{3}$$

The method accounts for variation of vertical tail planform(in particular the vertical tail span with fixed fuselage diameter), fuselage after-body shape, wing position and aspect ratio, horizontal tail position and size, see Figure 3. Results have been resumed in charts where it is clearly represented the variation of the aerodynamic interference factors with the aircraft geometrical parameters. By adding components to a given combination, the number of possible layout configurations increases. For this reason, there is 1 chart representing the effect of the fuselage, 3 charts that describe the effect of the wing, and 9 charts for the effect of the horizontal tail. As matter of fact, the nature of the CFD simulations has allowed to easily separate the effects and calculate the contribution to directional stability of each aircraft component. For more details see ref. [9].

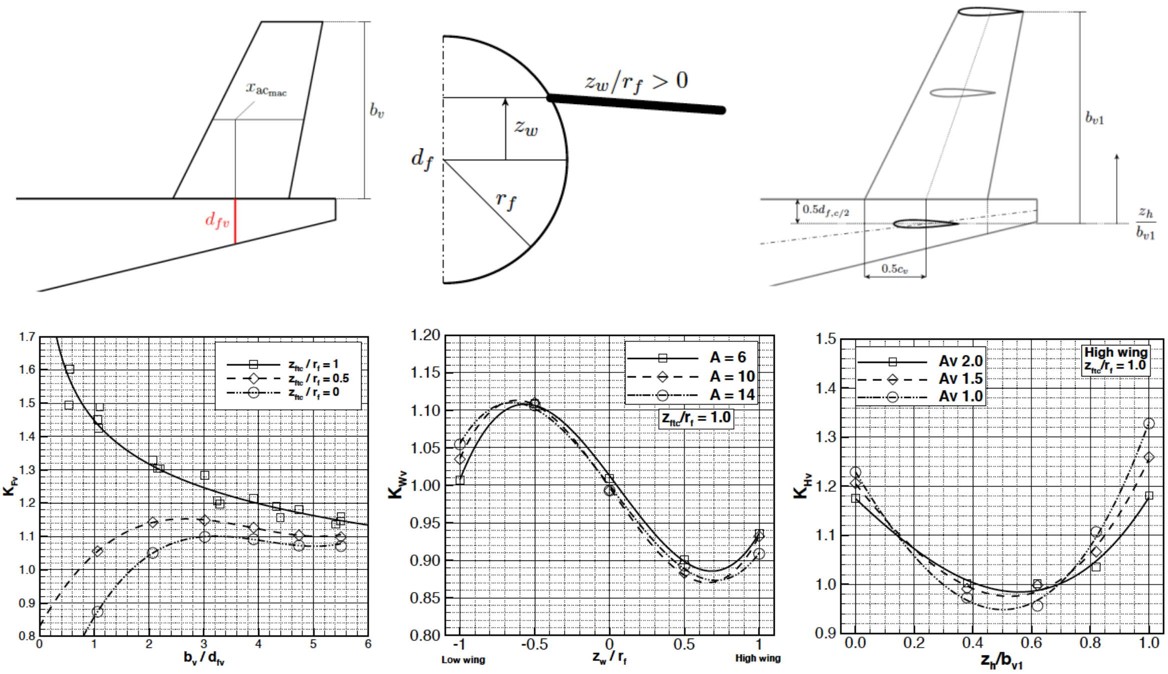
2.3 The new methodology - results

From all the aerodynamic results obtained through the broad CFD campaign several graph have been obtained (as previously mentioned). Only some of them are shown in Figure 4.
The Figure 4 shows how the above mentioned interference factors due to the fuselage (K_{F_v}), due to the wing-fuselage relative position (usually called sidewash) (K_{W_v}) and due to the horizontal tailplane vertical position (K_{H_v}) can be obtained for any different configuration. Figure 4a (left) shows the increment in vertical tail efficiency for different values of the parameter (b_v / d_f) and for different fuselage tailcone angles. It is worth to mention that the effct of the fuselage tailcone angle is usually not included in previous mentioned classical semi-empirical methodologies. Especially for $b_v/d_f < 3$ the effect of tailcone angle looks significant. The Figure 4b (center), shows the effect of the wing-fuselage relative position on the vertical tail stability contribution. This effect is usually also reported as sidewash [2, 10] and considered as a modification of the effective sideslip angle. In the graph is clearly shown that a low-wing arrangement leads to an increase of the efficiency of the vertical tailplane (as also is possible to estimate with the above mentioned classical methods). The third graph , Figure 4c (right) is representing the effect of the relative position of the horizontal tailplane to the vertical tailplane span. As also well-known from classical methodologies the body-mounted position and especially the T-tail arrangement lead to high positive values of the interference.
However, the present methodology, in case of a T-tail (z_h / b_{v1}=1.0) (h.tail mounted on the vertical tail) shows increment which seems slightly lower than this one proposed by classical semi-empirical methodologies. In the proposed graph the solid symbols refers to the analysed configurations, while the lines are presented as a best-fitting line to be used for any-other possible arrangements. The CFD calculations have been performed at low Reynolds number (i.e. between 0.5 and 1 million based on wing chord) and high Reynolds number(10 mil. based on wing chord) and in fully turbulent conditions. The effect of the Reynolds number has been found neglectable in the linear range of sideslip angle (for the estimation of the directional stability derivative), i.e. $\beta < 10$ deg. Similar approach has been developed for the estimation of the directional control derivative (rudder control power) and more details can be found in [7].

Concerning the fuselage contribution to aircraft directional stability (usually an unstable contribution) a dedicated similar work has been performed and published by the authors (see ref. [11]). The proposed method lead to an estimation of the fuselage derivative $C_{N_{\beta_f}}$ for any different values of the classical main geometrical parameters describing the fuselage (like fuselage fineness ratio and tailcone upsweep). Once the fuselage contribution is estimated, our proposed method need the interference of the vertical tailplane on the fuselage contribution to be included. Usually the classical semi-empirical methods (ESDU, Datcom) do not include any such interference because the wind-tunnel test results used to extract these methods were not able to separate the effects (only one general load cell was used on the model) without the possibility to separate the vertical tail force contribution. In general, once the isolated fuselage contribution is estimated (the method proposed in [11] is an alternative to other possible methods such as Multhopp implementation of Munk theory [12]) the fuselage contribution to aircraft directional stability is obtained through the following formula (4) where the two K-

factors are respectively the interference factor of the vertical tailplane on the fuselage aerodynamics K_{Vf} and the effect of non-linearities $K_{nl}(\beta)$ which lead to lower instability for sideslip angles higher than 10 deg (for angles of sideslip lower than 7-8 deg the K factor is practically equal to 1.0)
The graph showing in example the vertical tail interference factor on fuselage directional negative stability is reported in figure 5.

$$C_{N_{\beta_f}} = K_{Vf}\, K_{nl}(\beta)\, C_{N_{\beta_{f,iso}}} \quad (4)$$



(a) (b) (c)

Figure 4: Effects of the fuselage (a), wing (b), and horizontal tail (c) on the vertical tail aerodynamic contribution

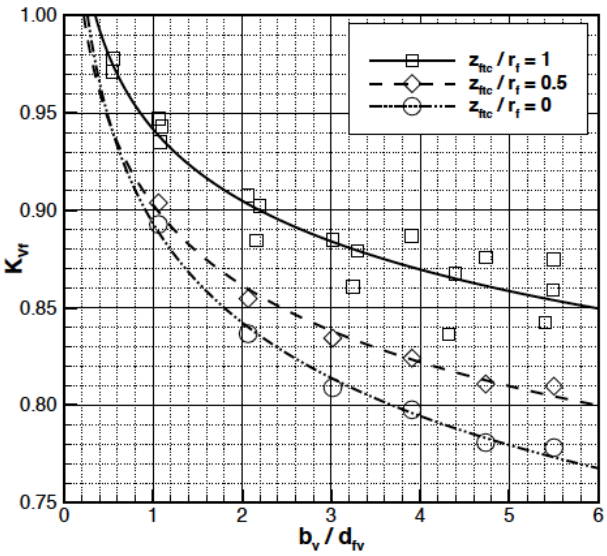


Figure 5: Effects of the vertical tailplane on the fuselage

2.4 The new methodology – wind-tunnel tests

A modular model to be tested in the low-speed wind-tunnel of the University of Naples has been also designed and built. Figure 6 and Figure 7 show the model installed in the test section and the load cell system able to measure both the global aerodynamic coefficients and the separate contribution of the vertical tailplane. Many configurations have been tested with the idea of validating the CFD analysis performed and used to build the new method. The comparison and validation has been performed at the same Reynolds number (about 0.5 mil. referred to the wing chord) and in fully-turbulent conditions (the model was equipped with a transition trip device on all aircraft components). As can be seen from Figure 8 a good agreement between numerical CFD results and experimental wind-tunnel test can be observed.

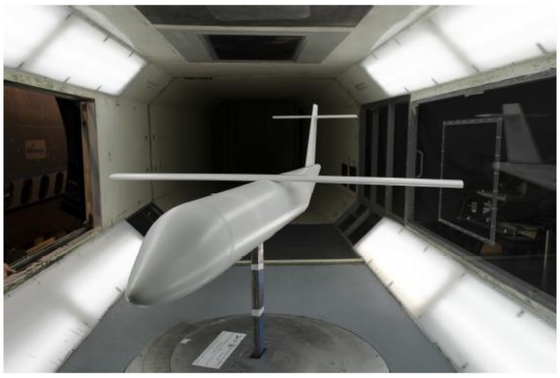


Figure 6: The aircraft modular model in the wind tunnel.

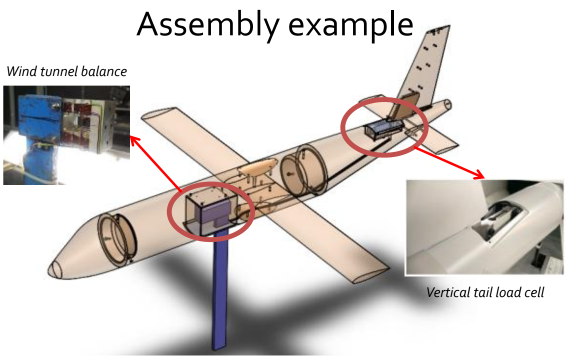


Figure 2: Balance and load cell locations.

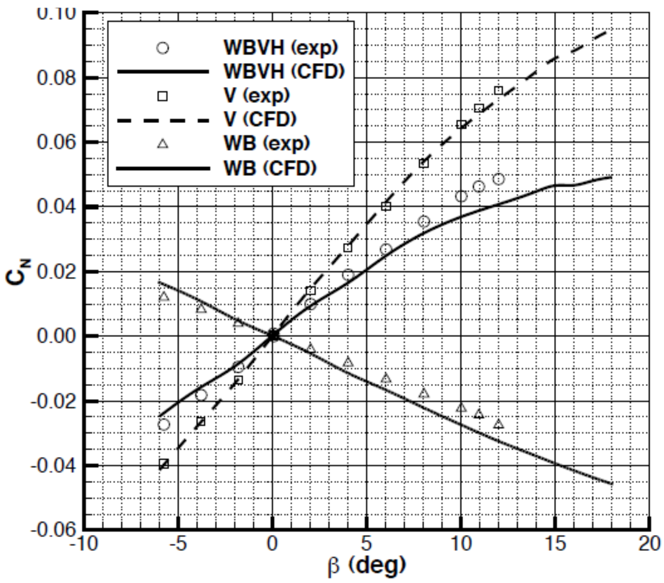


Figure 3: Comparison between CFD and wind tunnel experimental results.

Concerning the interference effects obtained through CFD analysis which represent the new proposed methods, the experimental wind-tunnel test results have indicated a quite good agreement with numerical CFD data. The Figure 9, in example, shows the interference effect of the horizontal tailplane position (previously shown in figure 4c). The lines refers to the best-fitting of CFD results while symbols represents the experimental wind-tunnel results for some tested configuration. The behaviour (influence of horizontal tailplane relative position) seems to be well captured, however some light discrepancy (lower than 4%) are present in some case (body-mounted or T-tail).

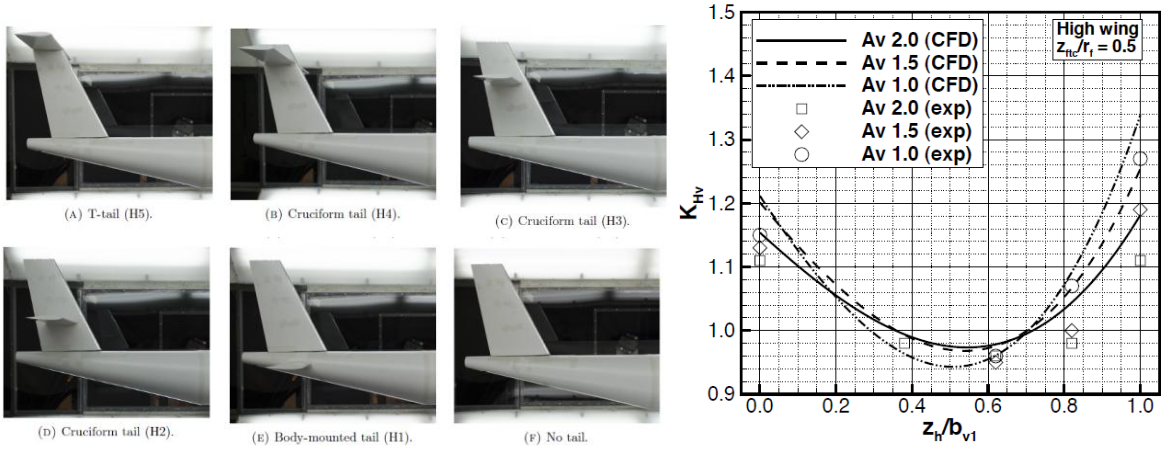
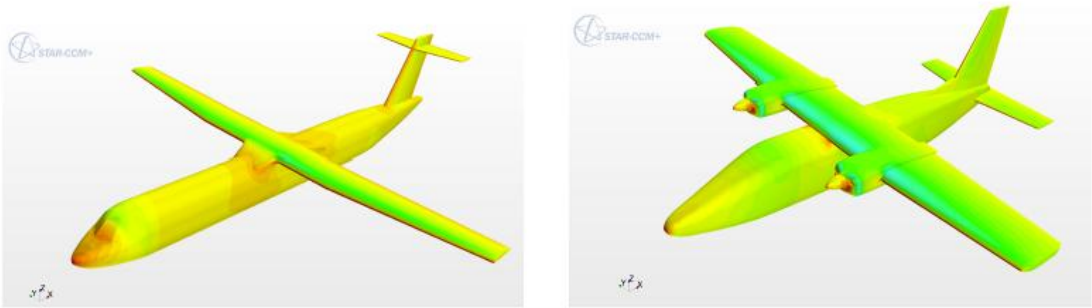


Figure 9: The proposed method compared to WTT experimental results.

3 APPLICATIONS

The proposed method (composed by graphs) to be used in preliminary design phase has been used to estimate the directional stability derivative of some generic configurations and results have been compared with the results obtined through classical semi-empirical methodologies (ESDU, Datcom).

For two different configurations the CAD model has been assembled and CFD calculations have been performed. The CFD RANS results have been considered as reference exact values (the difference in % is 0 in this case). For the P2012 aircraft also the experimental WTT (Wind-Tunnel Tests) results were available and were in very good agreement with CFD RANS results. Table 1 shows the results obtained for the generic Regional Turboprop configuration comparing the CFD results with the application of the two classical semi-empirical methods and the new method proposed by the authors. Results are reported separately for the vertical tailplane stability contribution and for the fuselage (unstable) contribution. It is possible to notice that, respect to the CFD results, the new proposed method presents differences lower than 1%, while Datcom and ESDU show differences higher than 10% with respect to CFD values. For the P2012 aircraft, results are reported in Table 2. The application of Datcom shows a difference higher than 30%, while ESDU and the new method are very close to CFD results.



(A) Generic Regional Turboprop. (B) Tecnam P2012.

Figure 40: Two configurations used to compare semi-empirical methods.

	Vertical tail		Fuselage	
	$C_{N\beta v}$ (/deg)	Δ%	$C_{N\beta f}$ (/deg)	Δ%
CFD	0.00426	-	-0.00218	-
DATCOM	0.00475	11.5	-0.00216	-0.65
ESDU	0.00490	15.0	n.a.	n.a.
New method	0.00421	-1.09	-0.00215	-1.29

Table 1: Results for the Generic Regional Turboprop.

	Vertical tail		Fuselage	
	$C_{N\beta v}$ (/deg)	Δ%	$C_{N\beta f}$ (/deg)	Δ%
CFD	0.00274	-	-0.00090	-
DATCOM	0.00187	-31.8	-0.00120	-33.0
ESDU	0.00273	1.1	n.a.	n.a.
New method	0.00255	-7.31	-0.00092	-2.20

Table 2: Results for the P2012 aircraft.

4 CONCLUDING REMARKS

This work has presented a new semi-empirical methodology to estimate in preliminary design the directional stability and control of an aircraft. The analysis and reliable estimation of the vertical tail contribution and the fuselage contribution to the directional stability of the aircraft is crucial in the implementation of a correct tail sizing and to guarantee the appropriate safety, performance, and flight qualities. The method has been developed through a wide CFD analysis campaign performed on a modular model. The numerical analysis have been validated through several wind-tunnel tests performed on the same modular model tested in the low-speed wind-tunnel of University of Naples. The final goal of the new method is to provide more reliable preliminary design methods for transport aircraft, especially for the regional turboprop category. The new method developed by the authors seems promising in comply with the objective and it has been also extended with data about rudder effectiveness for the correct estimation of rudder control power derivative which is crucial for V_{MC} analysis.

5 ACKNOWLEDGEMENTS AND REFERENCES

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